Application of satellite surface wind data to ocean wind analysis

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ABSTRACT

A new set of cross-calibrated, multi-satellite ocean surface wind data is described. The principal data set covers the global ocean for the period beginning in 1987 with six-hour and 25-km resolution, and is produced by combining all ocean surface wind speed observations from SSM/I, AMSR-E, and TMI, and all ocean surface wind vector observations from QuikSCAT and SeaWinds. An enhanced variational analysis method (VAM) performs quality control and combines these data with available conventional ship and buoy data and ECMWF analyses. The VAM analyses fit the data used very closely and contain small-scale structures not present in operational analyses. Comparisons with withheld WindSat observations are also shown to be very good. These data sets should be extremely useful to atmospheric and oceanic research, and to air-sea interaction studies.

Keywords: variational methods, ocean winds, marine, miocrowave radiometry, scatterometry, data processing

1. INTRODUCTION

July 1987 marks the beginning of an unprecedented period of remote sensing over the global oceans. Beginning with the launch of the DMSP SSM/I F08 satellite, the remote sensing coverage of the global oceans in a 6-hour period increased from 20% in 1987 to nearly 70% in 2004. From 1987 to 2007, over a dozen satellites became operational including both passive microwave sensors and scatterometers. (See Figure 1 for the temporal extent of the data sets analyzed in this work.) We previously described a variational analysis method (VAM) [1] that was used to combine wind speeds derived from the DMSP SSM/I satellites into a consistent global analysis at 1 x 1 degree resolution [2]. Under the NASA funded REASoN project, this work was significantly expanded. Cross-calibrated data sets produced by Remote Sensing Systems (RSS) and derived from SSM/I (F08 – F15), TRMM TMI, QuikSCAT, SeaWinds and AMSR-E were combined to create a consistent, long-term (1987 – 2007), global data set of ocean surface winds at high resolution (6 hours, 25 km). Available data from ERS-1, NSCAT, ERS-2, and WindSat were not used since these are not cross-calibrated with the RSS data sets used here. The new data products are currently available for interested investigators. Here we summarize the methodology, describe the data assimilated by the VAM, and introduce the products available for meteorological and oceanographic applications.

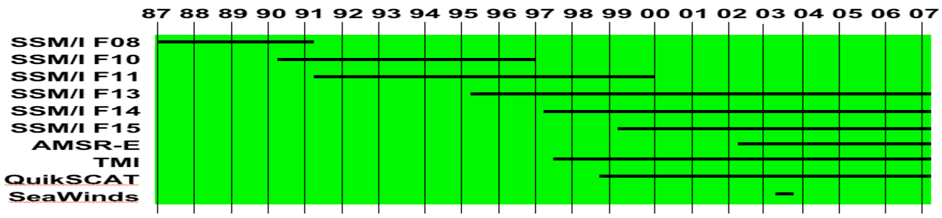

Figure 1. Time availability of satellite surface wind data sets analyzed by the VAM. The SSM/I instruments are denoted F08 through F15; SSM/I is the Special Sensor Mircrowave/Imager; AMSR-E is the Advanced Microwave Scanning Radiometer-E; TMI is the TRMM microwave imager; QuikScat and SeaWinds are scatterometers; the other instruments are microwave radiometers.

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2. METHODOLOGY

The VAM [1] that was previously used for the assimilation of SSM/I wind speeds has been enhanced for the assimilation of data from multiple platforms at high resolution. In previous work we treated SSM/I wind speed data as a special type of scatterometer data. Now we define a microwave ocean surface wind speed observation operator appropriate for SSM/I, TMI, AMSR-E, and other similar instruments. Considering each satellite individually allows us to weight each differently. The weights account for data density and data quality. We also reformulated the dynamical constraint to be the integral of the squared difference between the analysis and background time rate of change of vorticity at the surface. This is to avoid overly smoothing small-scale features in the analysis where the time rate of change of vorticity might be large.

The VAM analysis is defined to be the global grid of vector winds that minimizes

$$\begin{aligned} J \;=\;& \lambda_{\mathrm{CONV}} J_{\mathrm{CONV}} + \lambda_{\mathrm{SCAT}} J_{\mathrm{SCAT}} + \lambda_{\mathrm{SPD}} J_{\mathrm{SPD}} + \lambda_{\mathrm{VWM}} J_{\mathrm{VWM}} + \\ & \lambda_{\mathrm{LAP}} J_{\mathrm{LAP}} + \lambda_{\mathrm{DIV}} J_{\mathrm{DIV}} + \lambda_{\mathrm{VOR}} J_{\mathrm{VOR}} + \lambda_{\mathrm{DYN}} J_{\mathrm{DYN}} \end{aligned}$$

Here the λ are the weights, and the J are the individual cost function terms defined in Table 1.

REASoN products were assimilated at 25-km resolution on a 1/4 x 1/4 degree latitude-longitude grid. For comparison a 1 x 1 degree grid was used for the previous SSM/I Pathfinder data set [2]. As spatial resolution is increased, temporal scales must be resolved more accurately. The VAM was modified to perform the analysis at the observation times. This procedure is referred to as the First Guess at the Appropriate Time (FGAT). In areas of overlapping observations from multiple platforms, the linear approximation of the time tendency of the *u*- and *v*-components inherent in the FGAT procedure can lead to unrealistic analysis increments. Recognizing that data far from the analysis time is less valuable because of the assumption of linear in time variation of the wind components, the FGAT procedure was enhanced to effectively de-weight the data as the difference between the observation time and the analysis time increases.

Table 1. Observation functions and background constraints used in the VAM.

Term	Expression	Description of constraint
		Observation Function for the
J_{CONV}	$\sum(\mathbf{V}_\mathrm{A} - \mathbf{V}_\mathrm{O})^2$	• wind vectors
J_{SCAT}	$\sum(\mathbf{V}_\mathrm{A} - \mathbf{V}_\mathrm{O})^2$	• wind vectors
J_{SPD}	$\sum(\lvert\mathbf{V}_\mathrm{A}\rvert - \lvert\mathbf{V}_\mathrm{O}\rvert)^2$	• wind speeds
		Background Constraints on the
J_{VWM}	$\int(\mathbf{V}_\mathrm{A} - \mathbf{V}_\mathrm{B})^2$	• vector wind magnitude
J_{LAP}	$\int[\nabla^2(u_\mathrm{A} - u_\mathrm{B})]^2 + \int[\nabla^2(v_\mathrm{A} - v_\mathrm{B})]^2$	• Laplacian of the wind components
J_{DIV}	$\int[\nabla^2(\chi_\mathrm{A} - \chi_\mathrm{B})]^2$	• divergence
J_{VOR}	$\int[\nabla^2(\psi_\mathrm{A} - \psi_\mathrm{B})]^2$	• vorticity
J_{DYN}	$\int(\partial\zeta_\mathrm{A}/\partial t - \partial\zeta_\mathrm{B}/\partial t)^2$	• vorticity tendency

3. WIND DATA

The VAM requires a background (first guess) analysis of gridded u and v winds as an a priori estimate of the wind field. Analysis increments are added to this background to arrive at the final analysis. For this project, two data sets were used as the starting wind field. The 10-meter winds from the ERA-40 Re-analysis were used as a background for the period July 1987 to December 1998. Beginning in 1999, due to the benefits of 4d-VAR assimilation and increased spatial resolution, we made use of the ECMWF Operational analysis.

Satellite surface wind data were obtained from RSS under the DISCOVER project (Distributed Information Services: Climate/Ocean Products and Visualizations for Earth Research). RSS now uses a highly accurate sea-surface emissivity model resulting in much better consistency between wind speed retrievals from microwave radiometers (SSM/I, AMSR, TMI) and those from scatterometers (QuikSCAT and Seawinds). All observations are referenced to a height of 10 meters assuming that the boundary layer over the ocean is neutrally stable. Figure 1 shows the availability of satellite ocean surface wind products from RSS.

4. PRODUCTS

We produce three standard data sets, designated as level 3.0, 3.5 and 2.5. The primary data set, denoted Level 3.0, contains 6-hourly gridded VAM analyses. These analyses are time averaged over 5-day and monthly periods to derive the Level 3.5 data set. Only those grid points containing observations that passed quality control are used in the average to ensure that the time means represent the satellite climatology. Finally, directions from the VAM analyses are assigned to the wind speed observations for each microwave sensor to derive the Level 2.5 data set. All data sets share the same 25-km latitude-longitude grid.

5. VALIDATION

In order to validate our products objectively we examined both the analysis fit to assimilated observations and to independent observations from the WindSat mission. In general, we expect the VAM to fit the satellite ocean surface wind data better than the ECMWF (or other operational) analyses. This is in part due to the higher spatial resolution of the VAM analyses and also because not all the satellite data were used by ECMWF. It should also be noted that ECMWF used the ERS-1 and ERS-2 winds, which were not used by the VAM.

Figure 2 compares all observations used (i.e., those that passed quality control) within 30 minutes of the synoptic time to the VAM and to the ECMWF analyses as a function of time. Each point plotted in the figure corresponds to statistics accumulated over a single 5-day period (pentad). Note that the counts refer to all data used, while the directional rms is calculated for the scatterometer data only. The top panel shows that the VAM consistently fits all available data to ~0.5 m/s, while the ECMWF fit to the ocean surface wind data is roughly constant at 1.75 m/s during the period we use the reanalysis data and then slowly improves with time to 1.4 m/s during the period we use the operational analyses. The VAM fit of 0.5 m/s is a remarkable metric of the internal consistency of the RSS data. The 0.5 m/s value is considerably smaller than satellite buoy comparisons. However, satellite buoy comparisons suffer from representativeness errors, and buoy observation errors including height and stability adjustment errors. The second panel shows the rms directional difference between the scatterometer data and the analyses. Here we see that the VAM fits the data to about 8 degrees and the ECMWF analyses to about 15 degrees. In terms of wind speed bias, the VAM has no bias overall, while ECMWF is consistently 0.5 m/s slower than the satellite observations. The bottom panel (counts) shows the increase with time of the observational data base from one to 5-7 available satellite sensors.

Figure 3 compares the preliminary WindSat data to the VAM and ECMWF analyses. The WindSat data were not used by the VAM or ECMWF, only basic quality control was applied to the WindSat data, and just two months of data were used to prepare Fig. 3. Relative to WindSat the directional bias of the VAM is small, but the ECMWF winds are consistently biased positive by about two degrees. The same two-degree bias is found when comparing ECMWF winds to the scatterometer winds (not shown). Directional bias is defined here so that a positive bias means the wind is blowing more toward high pressure. The ECMWF positive bias is consistent with smoother and more geostrophic winds. We have often seen examples where the directional bias of the VAM is small, but the ECMWF

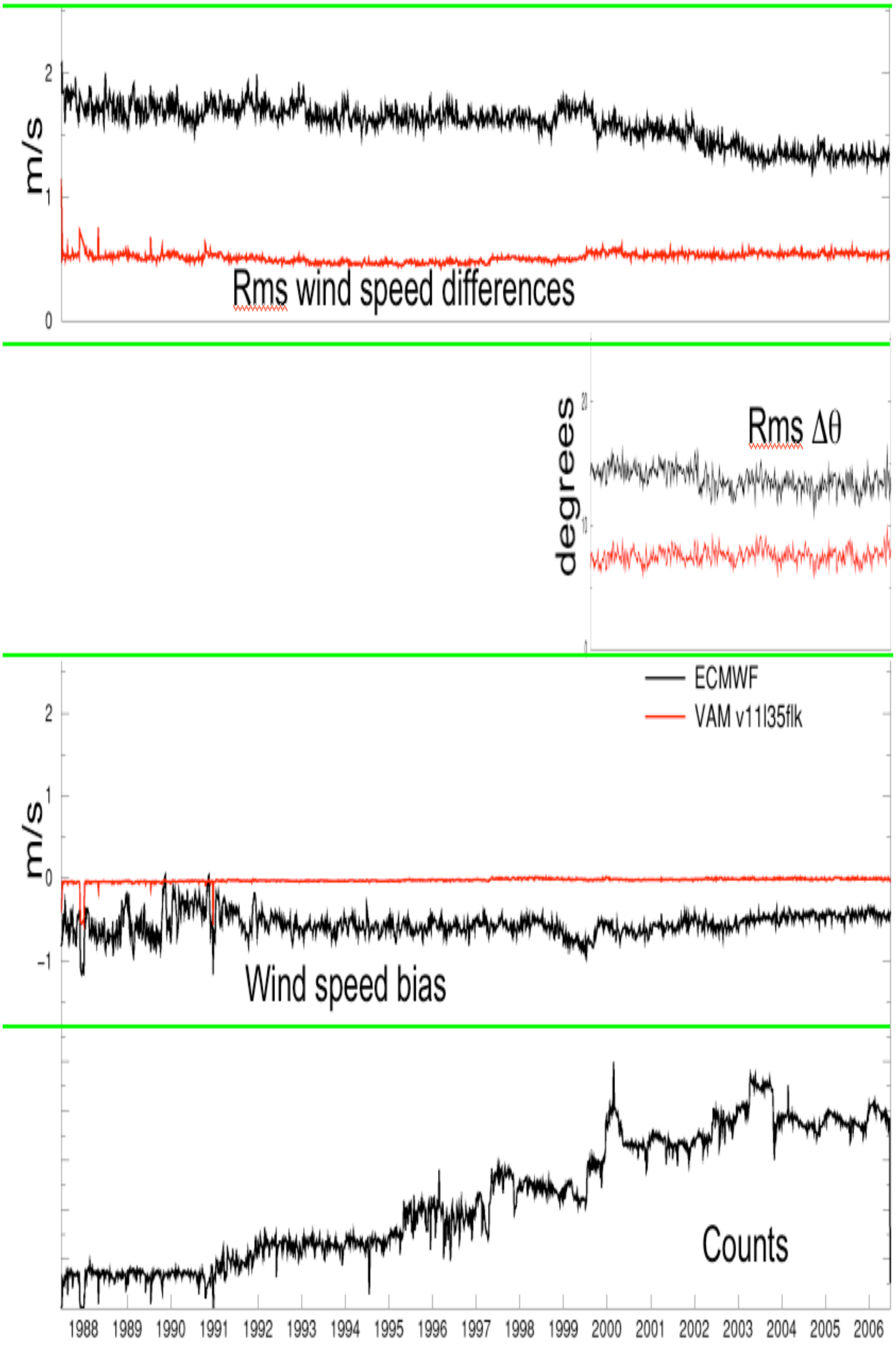

Figure 2. Comparison of fits of the ECMWF background (black) and VAM analyses (red) to all satellite observations used by the VAM within 30 minutes of the synoptic time. One point is plotted per pentad. Directional differences are calculated only for the available scatterometer data. Counts in the bottom panel are valid for the wind speed bias and rms differences and range from 500,000 to 3,000,000 per pentad. Scatterometer data counts per pentad are roughly 500,000 for each of QuikSCAT and SeaWinds.

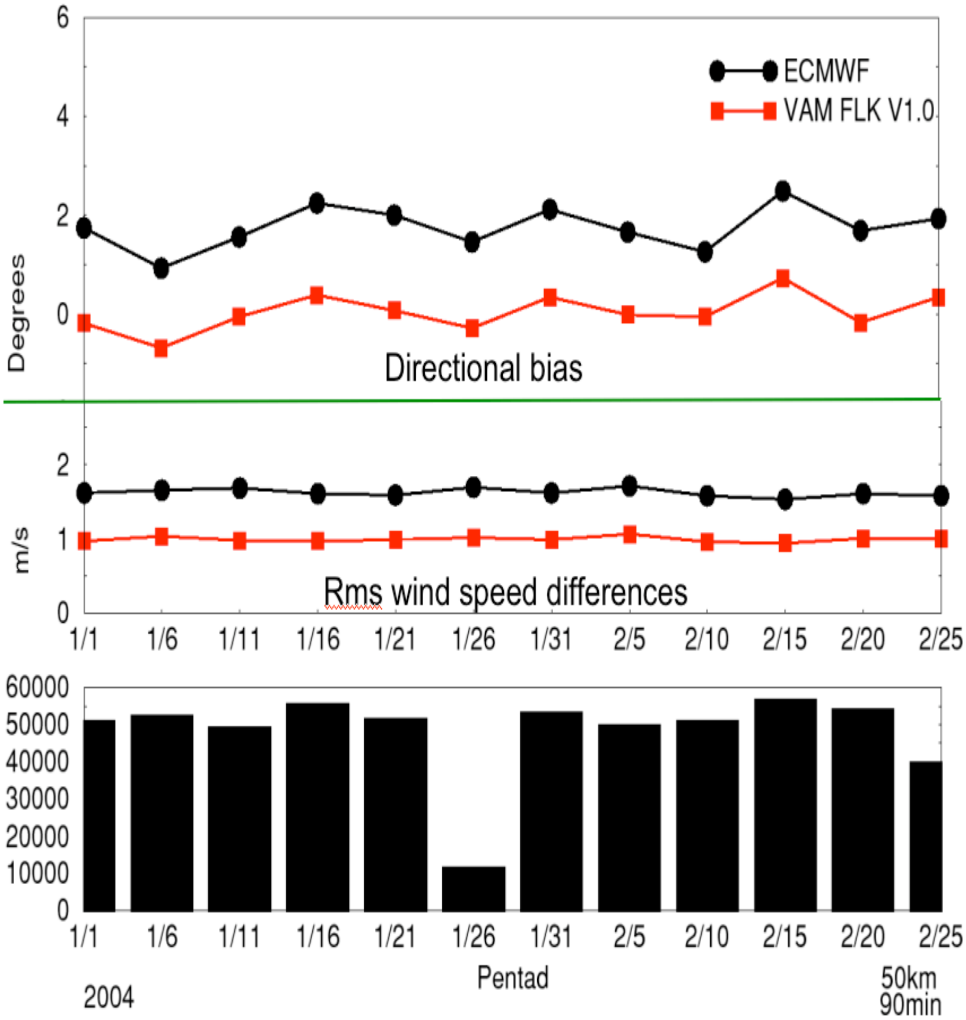

Figure 3. Comparison of fits of the ECMWF background (black) and VAM analyses (red) to WindSat preliminary wind vector retrievals for the beginning of 2004. These data were not used by the VAM. One point is plotted per pentad. Only data within 90 minutes of the analysis time are used here. The bottom panel shows counts.

winds are consistently biased positive by about two degrees. The same two-degree bias is found when comparing ECMWF winds to the scatterometer winds (not shown). Directional bias is defined here so that a positive bias means the wind is blowing more toward high pressure. The ECMWF positive bias is consistent with smoother and more geostrophic winds. We have often seen examples where the VAM winds are more ageostrophic, blowing more toward low-pressure centers, than the ECMWF winds. In terms of rms speed differences, the VAM fits the WindSat data to about 1 m/s, while the ECMWF analyses only fit these data to about 1.75 m/s. The rms directional differences for both are about 22 degrees (not shown).

Figures 3-4 show an example of the differences that can occur between the ECMWF background field and VAM analyses. Here, MODIS imagery (figure 3) depicts two cyclone centers in the North Pacific. Comparison of the ECMWF and VAM wind streamlines (figure 4 top) shows that both of these cyclone centers are present in the VAM winds but not in the ECMWF background. The wind speed differences are also very substantial, with the VAM showing higher wind speeds and greater structure (figure 4 bottom).

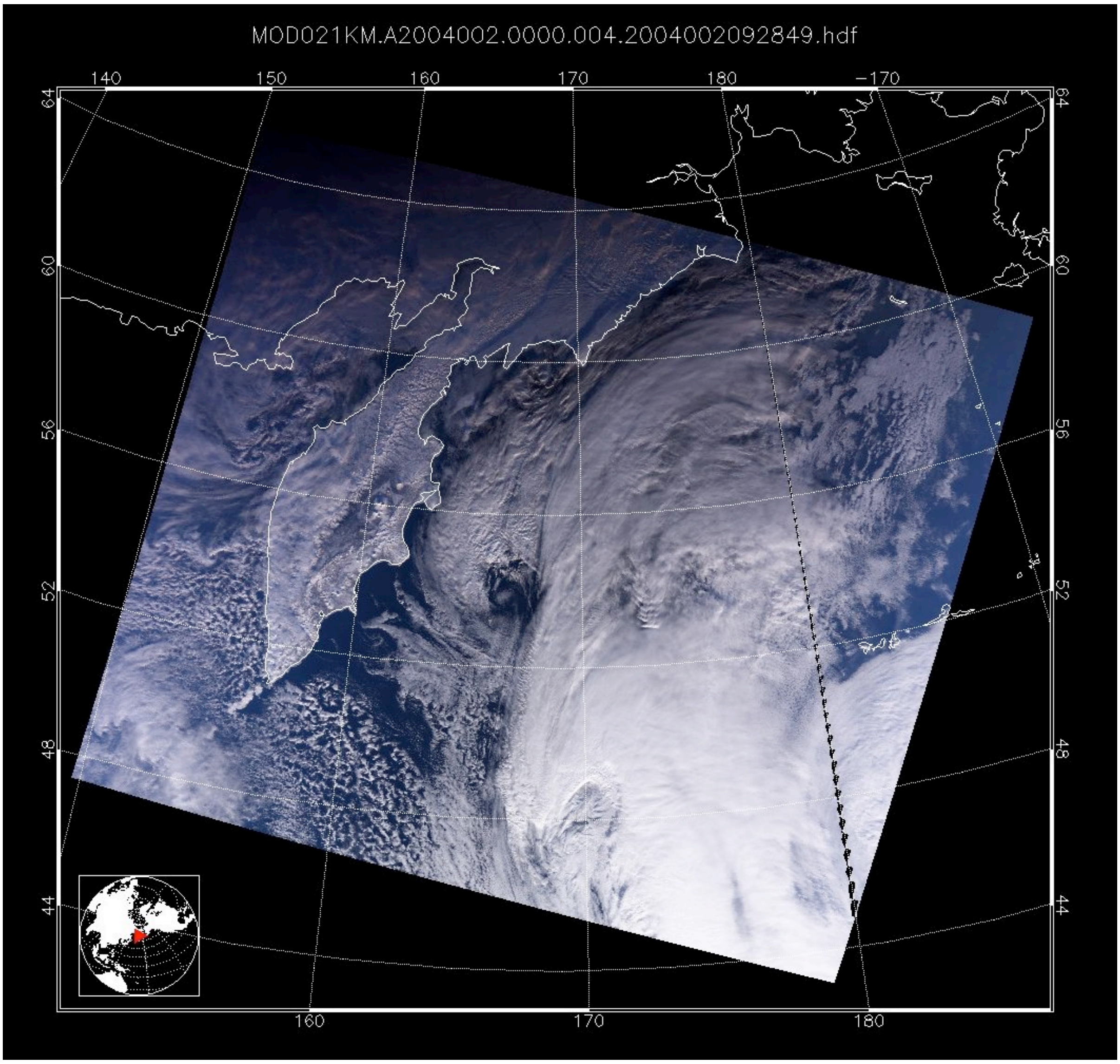

Figure 3 MODIS imagery over a portion of the North Pacific on January 2, 2004.

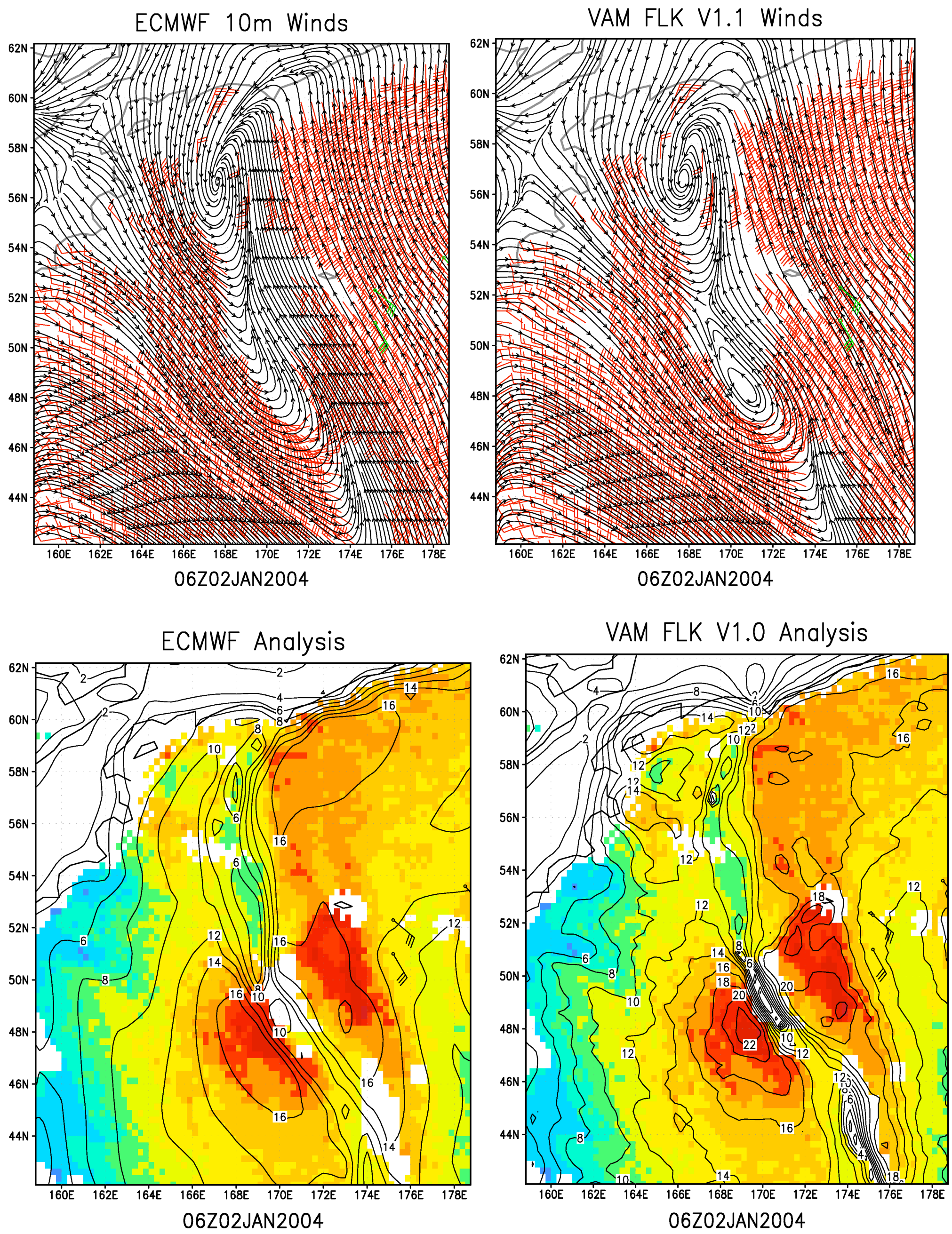

Figure 4 Comparison of ECMWF and VAM winds on January 2, 2004

6. SUMMARY

An enhanced variational analysis method (VAM) has been used to combine the latest RSS cross-calibrated, multi-satellite data sets of ocean surface wind. In this way we uniformly combine all available surface wind speed observations from SSM/I, AMSR-E, and TMI, and all ocean surface wind vector observations from QuikSCAT and SeaWinds with the best ECMWF analyses. The VAM analyses cover the global ocean for the period beginning in 1987 with six-hour and 25-km resolution. The analyses fit the data used very closely, with significant improvements in the location and structure of meteorological features. Comparisons with withheld WindSat observations are also very good. The VAM analyses are used to assign directions to the microwave radiometer wind speed data sets. Pentad and monthly average data sets are also available.

7. ACKNOWLEDGEMENTS

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